$C_6H_{12}O_6 + 36Pi + 36ADP + 6O_2 + 6H_2O \longrightarrow 6CO_2 + 36ATP + 12H_2O$

686,000 calories

1. RESPIRATION

2. 6 C —Broken down into→ 3 C

Hexose Sugar → Pyruvic acid & NADH (coenzyme) (or reduced NAD)

3. Pyruvic acid —enters→ Mitochondria for complete oxidation into CO_2 & water

→ This **Metabolic pathway** is grouped under

1) Glycolysis / EMP / EMPP Pathways (Embden. Meyerhof. Parnas)
2) Oxidative decarboxylation
3) Krebs Cycle / Citric acid cycle / Tricarboxylic acid cycle (TCA)
4) Respiratory Chain (ETS) & Oxidative Phosphorylation

- Independent of light
- Takes place in Mitochondria
- Uses molecular O_2
- Exergonic reaction
- (Liberates CO_2 & H_2O)
- (Complete breakdown of Food)

Foodstuff + O_2 → CO_2 + H_2O + Energy

1.) Glycolysis in anaerobic condition

Under
Anaerobic conditions:

Pyruvic acid $\xrightarrow[+NADH]{\text{Lactic dehydrogenase}}$ Lactic Acid + NAD + Energy

remains in Cytosol

& accepts Hydrogen from NADH

∴ Full anaerobic reaction from Glucose breakdown is

$$C_6H_{12}O_6 + 2ADP \longrightarrow C_3H_6O_3 + 2ATP + H_2O$$

(Lactic acid)

In Yeast (Saccharomyces cerevisae) anaerobic respiration is called Alcoholic Fermentation & pyruvic acid is converted to Ethyl alcohol via acetaldehyde.

Glucose $\xrightarrow{\text{Glycolysis}}$ Pyruvic acid $\xrightarrow[\text{(oxidative decarboxylation)}]{-CO_2}$ Acetaldehyde $\xrightarrow{+2H}$ Ethyl alcohol

But in Higher plants in - O_2 (anaerobic condition)

Pyruvic acid is converted to either Ethyl Alcohol OR Any Organic Acid (Malic acid / Citric acid / Oxalic acid / Tartaric acid)

Difference:

Fermentation is an extracellular process in Yeast & requires sugar + liquid medium

Anaerobic respiration is intracellular

Zymase enzyme is required for both.

∴ $$C_6H_{12}O_6 \xrightarrow[\text{OR Fermentation}]{\text{Anaerobic respiration}} 2C_2H_5OH + 2CO_2 + \text{Energy}$$

28 Kcal

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Glycolysis in aerobic condition

1. Final product is → Pyruvic acid & coenzyme NADH
2. Enzymes used up — (10)
3. Location — Cytosol (Cytoplasmic matrix)

Glycolysis is subdivided in 3 steps:

1.) Activation (Stage I) :- 3 steps

1 to 3 Glucose molecule → Fructose-1-6-diphosphate

2 ATP used up → ADP + P_i

Series of steps requires [3] enzymes.
- Hexokinase
- Phosphoglucose isomerase
- Phospho fructo kinase

4 to 5

2.) Cleavage (Stage II) :- Only 1 step

Fructose-1-6-diphosphate —splits into→ 2 molecules of Glyceraldehyde-3-Phosphate (3 Carbon Compound)

Only [2] enzymes required
- Aldolase
- Triosephosphate isomerase

6 to 10

3.) Oxidation (Stage III) :- 4 steps

2 mole Glyceraldehyde-3-Phosphate —is Oxidised→ NADH + 2 mole Pyruvic Acid.

4 ADP + P_i → 4 mole ATP produced ↑

5 enzymes:
- Phosphoglyceric dehydrogenase
- " Kinase
- " mutase
- Enolase
- Pyruvic Kinase

4 ATP molecules generated by Substrate-level-phosphorylation.

★ Glycolysis :- Occurs in both Aerobic & Anaerobic

Location :- Cytoplasm

Reactant :- 1 Glucose (6 C), 2 NAD^+, 2 ADP

Products : 2 mol Pyruvic Acid (3 C), 2 NADH, 2 ATP.

1.) Glucose
ATP → ADP | Hexokinase + Mg^{++}

2.) Glucose-6-Phosphate ($C_6H_{11}O_6-P$)
↓↑ Phosphohexo isomerase + Mg^{++}

3.) Fructose-6-Phosphate ($C_6H_{11}O_6-P$)
ATP → ADP | Phosphofructo kinase + Mg^{++}

Glucose & Fructose are Phosphorylated to give Glucose-6-Phosphate & Fructose-6-" . ATP is used.
Isomerises to Fructose-6-Phosphate ↓ is phosphorylated

4) Fructose 1-6-diphosphate
| Aldolase
Splitting / Cleavage

5) 2 molecules (3-Phosphoglyceraldehyde) Glyceraldehyde-3-Phosphate (3 C) [PGAL] ($C_3H_5O_3-P$) ⇌ Dihydroxy acetone Phosphate (3 C) [DiHAP]
NAD^+ → 2NADH | glyceraldehyde phosphate dehydrogenase

6) 2 molecules 1,3-diphosphoglyceric acid ($P-C_3H_6O_4-P$)
2ADP → 2ATP | Phosphoglycerate kinase

Energy Conserving phase - Glyceraldehyde ↓ oxidised to Carboxylic Acid

ATP generated

7) 2 mole 3, Phosphoglyceric acid (2 molecules of $C_3H_4O_4-P$)
Isomerisation | Phosphoglyceromutase + Mg^{++}

→ATP is generated by transfer of (P_i) phosphate group from substrate to ADP.

8) 2, Phosphoglyceric acid
Dehydration | Enolase Mg^{++} → H_2O

9) 2 mole Phosphoenol Pyruvic acid [PEP] (2 molecules of)
ATP generated: 2ADP → 2ATP | Pyruvate Kinase Mg^{++}

10) 2 mole Pyruvic acid (2 molecules of) (3 Carbon Compound) $C_3H_4O_3$

ATP generation during glycolysis is by:
- Substrate level phosphorylation — Transfer of phosphate group to ADP
- Oxidation of NADH to NAD^+ (1 NADH → 3 ATP; 2 NADH → 6 ATP)

Net gain of ATP (Glycolysis)

1) 4 ATP molecules are formed.
2. Out of 4 ATP molecules, 2 ATP molecules are utilised (consumed) in the beginning
   Net gain → 2 ATP
3. Oxidation of 2 NADH produces 6 ATP (1 NADH → 3 ATP; 2 NADH → 3×2 ⇒ 6 ATP)
4) During glycolysis (4 − 2) + 6 = 8 ATP

⇒ During Anaerobic respiration
$NADH + H^+$ is not converted to ATP
∴ Only 2 ATP molecules are produced.

→ Pyruvic Acid still contains large amt. of energy
→ It undergoes degradation by 3 processes in MITOCHONDRIA
a.) Oxidative decarboxylation of Pyruvic Acid
b.) Kreb's cycle
c.) Oxidative phosphorylation (Electron Tranport System)

a.) Pyruvic acid enters mitochondria
→ One of its 3 Carbon atom is oxidised to CO_2.
→ So, Pyruvate is decarboxylated first then it is oxidised by enzyme pyruvate dehydrogenase.
(it contains ↓) Decarboxylase, Lipoic acid, TPP (Thiamine pyrophosphate), Transacetylase & Mg^{2+}

Pyruvic acid + NAD^+ + Co-A ——→ 2 molecules Acetyl Co-A (2 Carbon) + NADH + H^+ + CO_2 ↑

Pyruvic acid converts to 2 mole Acetyl Co A.

2 NADH molecules (produced in Glycolysis) does not penetrate Mitochondria

Only their e^- are transferred to Dihydroxy acetone which ~~that~~ takes them in & out of Mitochondria

ATP is required for above process

1 ATP for 1 NADH (in all 2 ATP used up)

These (2NADH) when pass through ETS they produce 6 ATP molecules

Citric Acid Cycle / Tri Carboxylic Acid

Kreb's Cycle :

1st step is condensation, 2 decarboxylation & 4 dehydrogenations

2 mole Acetyl CoA enters Mitochondrial Matrix

1st Step :
Condensation of acetyl group with 4-Carbon Oxaloacetic acid (OAA) to make (6-Carbon compound) Citric Acid.

Location : Mitochondrial Matrix
Substrate : 2 molecules Acetyl CoA, 6 NAD^+, 2 $FADH^+$, 2 ADP

Products : (4) ~~6~~ CO_2 (actually in Kreb's cycle / overall), 6 NADH, 2 $FADH_2$, 2 ATP

→ Oxidation of 1 Pyruvic acid molecule → (2) ~~3~~ CO_2 molecules are released (∴ 4/6 CO_2 ??)

→ 2 turn of Kreb's cycle completely oxidise (break up) 1 glucose molecule (or metabolize 2 acetyl groups)

→ Only 2 ATP molecules are produced.

→ Glucose breakup frees Hydrogen atoms attached to Carbon.

→ Each Hydrogen atom has 1 proton (H^+) & 1 electron (e^-)

$2H \rightarrow 2H^+ + 2e^-$

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→ At each turn of Krebs Cycle

✱ 4 pairs of hydrogen atoms are removed from the Substrate intermediates by enzymatic dehydrogenation. & 2 molecules of CO_2 ↑ released.

In 2 turns → 8 pairs Hydrogen atoms (required)

→ These Hydrogen atoms (or pairs of e^-) enter ETS & are accepted by either NAD^+ or FAD.

✱ 3 pairs H_2 molecules accepted by NAD^+ → NADH

1 pair H_2^+ FAD → $FADH_2$

Oh Citric acid Is Of course A (alpha) Silly Stupid Funny Molecule.

water in
Water out
Water in
NADH released
CO_2 (both
NADH – CO_2 "
Gossip "
FADH "(4)
Water in
NADH (4)

Pyruvate (Pyruvic acid)

Pyruvate dehydrogenase: NAD^+ → NADH+H^+; CoA; → CO_2

Fatty acid, Amino acid →

Acetyl CoA

Condensation

Acetyl CoA + Oxaloacetate ($C_4H_4O_6$) —condensing enzyme, H_2O, → CoA→ Citric acid ($C_6H_8O_7$)

Dehydration: Citric acid → H_2O (Aconitase) → Cis-aconitic acid ($C_6H_6O_6$)

Isomerised to

Rehydration: Addition of H_2O catalyzed by Fe containing enzyme

Cis-aconitic acid + H_2O (Aconitase) → Iso-citric acid ($C_6H_8O_7$)

Oxidation: Iso-citric acid — NAD^+ → NADH+H^+ (Isocitric dehydrogenase + Mn^{++}) → Oxalo succinic acid

De-carboxylation: Oxalo succinic acid → CO_2 → α-Ketoglutaric acid ($C_5H_6O_5$)

Oxidation—Decarboxylation: α-Ketoglutaric acid — CoA, CO_2, NAD^+ → NADH + H^+ (α-Ketoglutarate dehydrogenase) → Succinyl CoA

Phosphorylation: Succinyl CoA — ADP (GDP+Pi) → ATP (GTP); CO_2 (Succinyl CoA Synthetase + Mg^{++}) → Succinic acid ($C_4H_6O_4$)

Oxidation: Succinic acid — FAD → $FADH_2$ (Succinic dehydrogenase) → Fumaric acid ($C_4H_4O_4$)

Hydration: Fumaric acid + H_2O (Fumarase) → Malic acid ($C_6H_6O_5$)

Oxidation: Malic acid — NAD → NADH+H^+ (Malic dehydrogenase) → Oxaloacetate

Respiratory Chain or Electron Transport System.

Summary:

Location : Inner Mitochondrial membrane

Substrate ; 10 NADH , 2 $FADH_2$, 6 O_2 , 34 ADP

Products : 10 NAD^+ , 2 FADH , 6 H_2O , 34 ATP

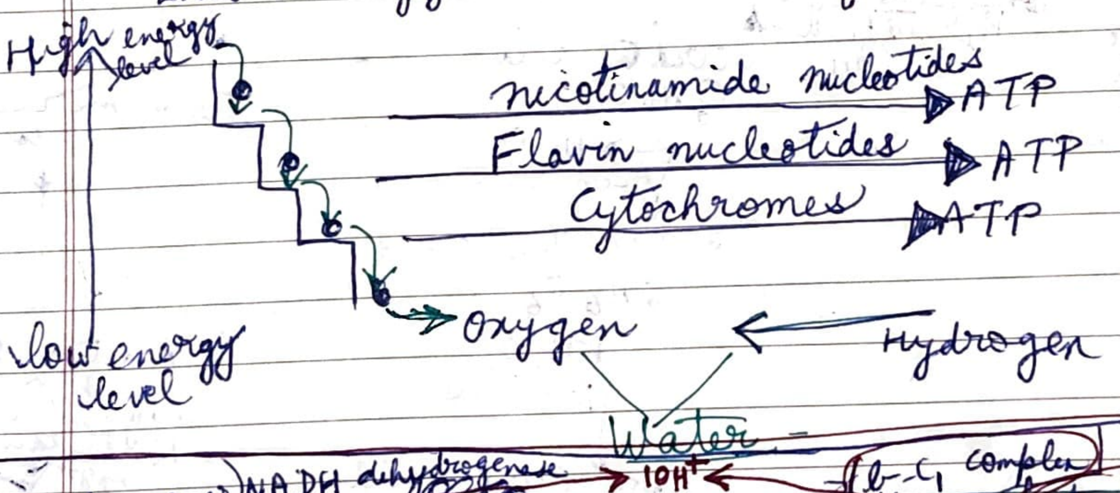
→ Final e^- acceptor is molecular O_2.

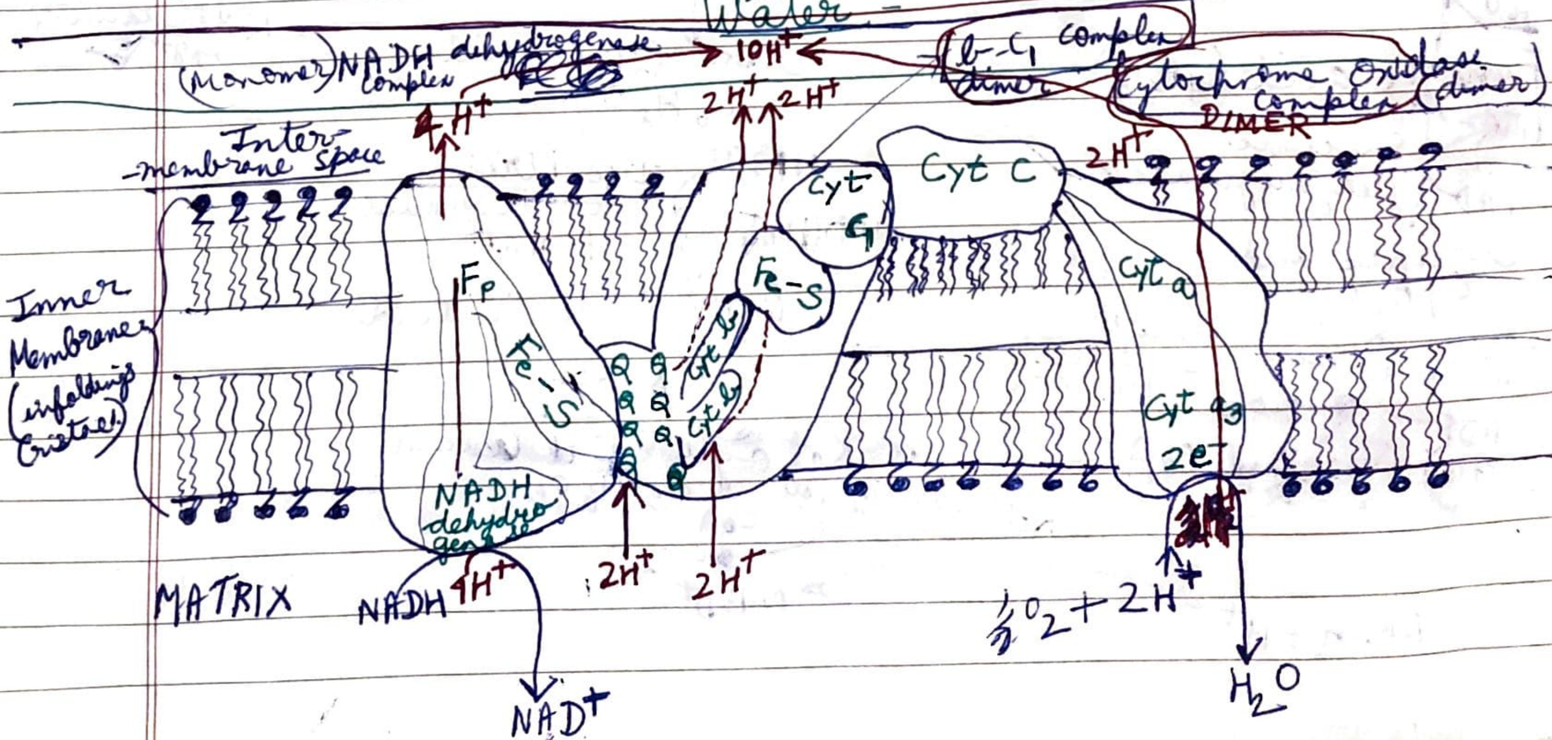
→ passage of e^- from NADH to O_2 —generates→ 3 ATP molecules

→ " " " " FADH to O_2 ⟶ 2 ATP molecules.

→ e^- are transferred to e^- acceptors at lower energy level. with each cascade the e^- release their Potential energy.

→ This energy is used to form ATP.



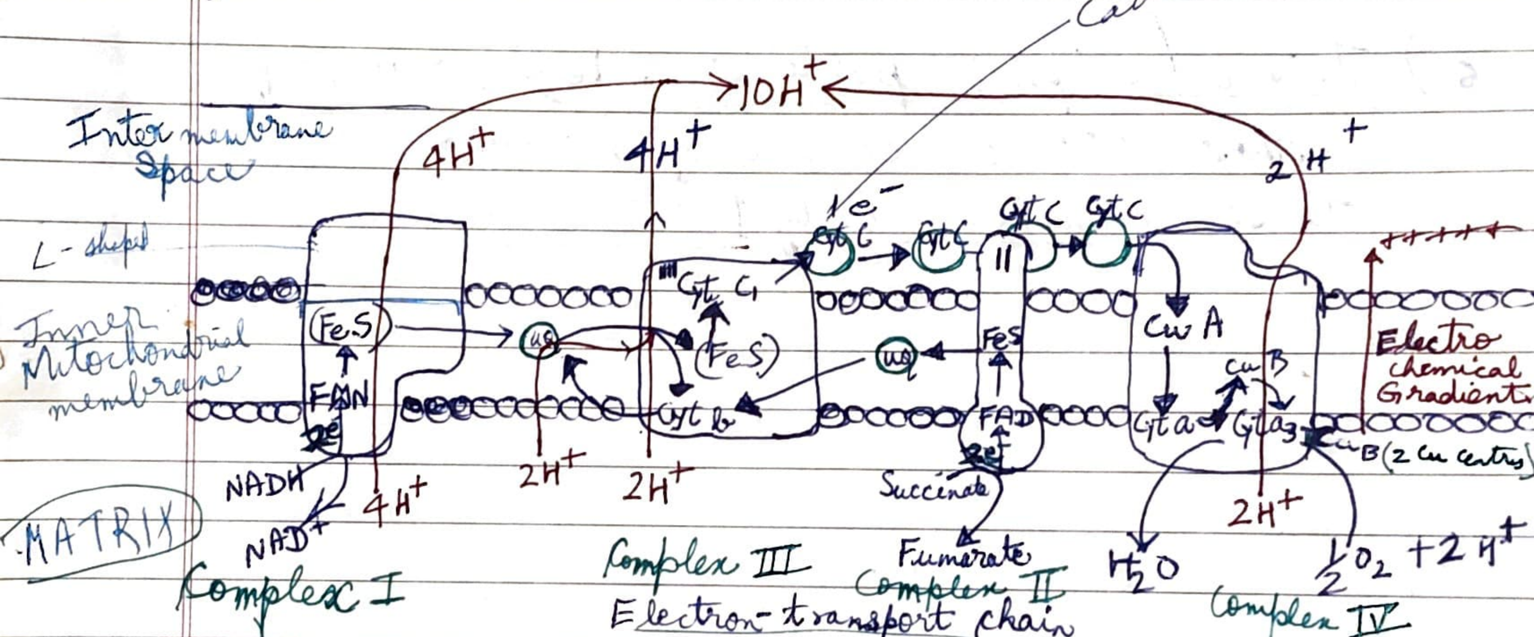


In matrix total 10 NADH is produced (2 NADH → Glycolysis; 2 NADH → (Pyruvate → Acetyl Co A); 6 NADH → Kreb's cycle)
total 2 $FADH_2$ " "

→ ETS consists of a series of Coenzymes & Cytochromes.

→ Electron (compounds) carriers include Flavins[1], Iron-sulphur complexes[2], Quinones[3] & Cytochromes[4].

NAD, FAD, 4 & 2 recipies



5 types of Compounds occur in ETS

1) Pyridine-linked dehydrogenases: their coenzyme NAD^+ accepts $2e^-$ at a time.

2) Flavin-linked dehydrogenases (Flavoproteins): require either FAD or FMN. Both can accept two hydrogen atoms.

3) Ubiquinones: (chemical resemblance to quinones) present in Mitochondria is Coenzyme Q 10 (CoQ_{10} or Q). It is a Lipid & accepts two hydrogen atoms ($2H^+$ & $2e^-$) at a time

4.) Cytochromes : are proteins having iron-porphyrin groups.
Mitochondria have 5 types of Cytochromes in inner membrane arranged in order,
Cyt b , Cyt c_1 , Cyt c , Cyt a & Cyt a_3.
All transfer e^- by reverse valance change of iron atom (Ferric to Ferrous).

transfers 1 electron at a time

5.) Iron - Sulphur proteins : (Fe_2S_2 & Fe_4S_4)
these are e^- carriers of mitochondria
These transfer only 1 e^- at a time.

Complexes of ETS.

Complex I — NADH dehydrogenase complex (NADH oxido-Reductase)

L-shaped. Consists of NADH-dehydrogenase. It contains (Flavoprotein FMN (flavin mononucleotide), associated with (Fe-S) proteins. (complex because)

This complex transfers $2e^-$ at a time & $2H^+$ from mitochondrial NADH to UQ

NADH $\xrightarrow{2e^-}$ FMN $\xrightarrow{2e^-}$ (5) Fe-S centre $\xrightarrow{2e^-}$ Q $\xrightarrow{2e^-}$ Cyt b – c_1 complex

Complex II

has removes H_2 from Succinate $\xrightarrow{\text{oxidised it to}}$ Fumarate

Succinate dehydrogenase complex which contains + Flavoprotein FAD (Flaven adenine dinucleotide) & Fe-S protein (cluster).

The complex receives e^- (also H^+) from Succinic acid (was oxidised to fumaric acid in Kreb's cycle) then passes it to Ubiquinone, which also receives e^- from $FADH_2$ produced. It is also a step in Kreb's cycle.

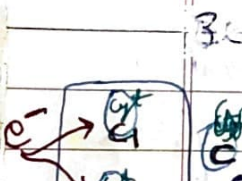
Complex III (Q H_2 – Cytochrome reductase complex)

Q – Cytochrome C oxido reductase

contains → Ubiquinol, Cytochrome C, Cytochrome b, Cytochrome C_1. Cytochromes have heme complexes + Iron-S core

Receives e^- from Ubiquinol which transfers e^- to → Cyt C via Cyt b & Cyt C_1

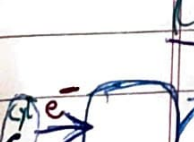
~~Basic components → Cyt b, ... (Fe-S) proteins, Cty C_1.~~



Coenzyme Q is involved between Fe S & Cyt C_1

Then Cyt C_1 $\xrightarrow[\text{transfers to}]{e^-}$ Cyt C. (mobile carrier of electrons between Complex III & Complex IV)

Complex IV (Cytochrome C oxidase complex) Heme & copper Units



Cytochrome a & Cytochrome a_3 along with 2 Copper centres.

Complex receives e^- from Cyt C & passes e^- to $\frac{1}{2}O_2$.

(Cyt C $\xrightarrow{e^-}$ Complex IV $\xrightarrow{e^-}$ $\frac{1}{2}O_2$).

$2H^+$ are needed & H_2O molecule is formed.

Here O_2 is ultimate acceptor of electrons. It combines with protons to form metabolic water.

2 Ferrocytochrome (Fe^{++}) + $2H^+$ + $\frac{1}{2}O_2$ ⇌ 2 Ferri Cytochrome C (Fe^{+++}) + H_2O.

Complex V (ATP Synthase complex) Coupling Factor.

Consists of 2 major components F_0 & F_1.

F_0 - complex → is an integral membrane protein complex.

It forms the channel through which protons cross the inner membrane.

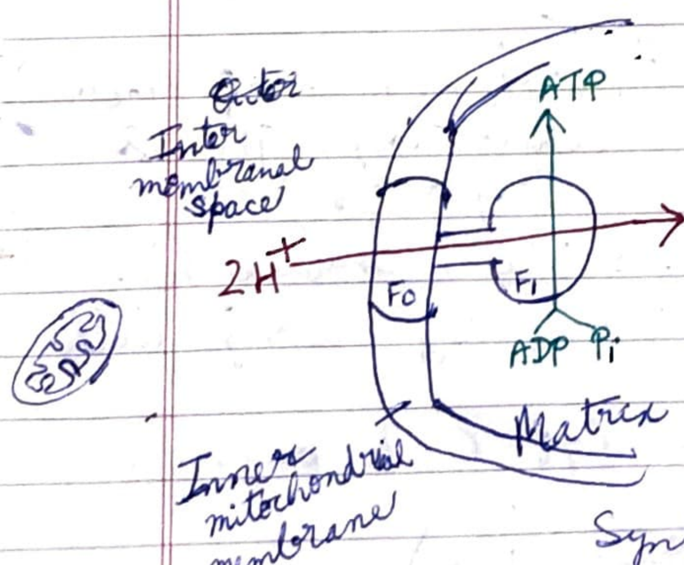
It possesses proton translocating mechanism.

F_1 - Complex → is attached to Fo complex.

→ It is the headpiece or Knob that protrudes on the matrix side of inner mitochondrial membrane.

→ It has 5 polypeptides (α, β, γ, δ, ε epsilon)

→ It contains the site for ATP production from ADP & (Pi) inorganic phosphate



H_2 ⇌ $2H^+ + 2e^-$

Synthesis of ATP.

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Oxidative phosphorylation :

The whole process, where O_2 allows the production of ATP by phosphorylation of ADP is called oxidative phosphorylation.

Synthesis of ATP → Phosphorylation

$$2H \rightleftharpoons 2H^+ + 2e^-$$

$$NAD^+ + H^+ + H^+ + e^- + e^- \rightarrow NADH + H^+$$

→ Each complex acts as an energy conversion device.

→ they harness the free energy released when electrons are transferred from one electron carrier to the other [illegible] (at low energy level)

→ It uses to pump H^+ across the inner mitochondrial membrane into inter membrane space. As a result an electro chemical proton gradient is created across the inner mitochondrial membrane.

~~Each protein complex has a vectorial organisation in the IMM, so all protons are pumped out of the matrix in the same direction.~~

→ Inner mitochondrial membrane is impermeable to both H^+ & OH^- ions. While H^+ is ejected [illegible] out, OH^- ions remain in Matrix.
∴ There is lower pH on inner membrane space & higher pH on matrix side. This results in electrical potential gradient.

→ The gradient provides force for inward transport of phosphate as well as for generating ATP.

→ Thus Proton pump of $F_0 - F_1$ drives oxidative phosphorylation of ADP into ATP.

$$ADP + P_i \rightleftharpoons ATP + H_2O$$

NAD

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→ F_o forms the channel through which protons cross the inner membrane into matrix. During this protons are coupled to the catalytic site of F_1 (ATP synthetase) & ATP is produced.

Oxidation of 1 molecule of NADH —produces→ 3 ATP molecules
" " 1 molecule of $FADH_2$ —"→ 2 ATP molecules

Pentose Phosphate Pathway /
Hexose Monophosphate Shunt (HMP Shunt) /
Phospho gluconate Shunt /
Warburg – Limpam – Dickens Cycle.

2 Phases
(i) Oxidative phase
(ii) (Non-oxidative phase)
(→ Sugars are interconvertible)

Location : In Cytosol.
Substrate : 6 molecules of Glucose-6-phosphate
Product : Complete oxidation of 1 molecule of glucose —produces→ 12 molecules of NADPH (equivalent to) (12 × 3 ATP) = 36 ATP molecules

co-enzyme ↓ NADP

So this is also an effective alternative pathway for aerobic respiration of Glucose or oxidation of Glucose.

★ → No ATP is consumed or Produced

→ Alternative pathway for Carbohydrate metabolism (degradation).
→ Pentose Sugar Formed.
→ NADPH molecules are generated. These are used as reductants in biosynthetic processes (when NADPH molecules are not generated) by Photosynthesis.

★ → It is imporant pathway for non-photosynthetic tissues like germinating seeds, for differentiating tissues, (liver, adrenal glands, erythrocytes, adipose tissue) during period of darkness.

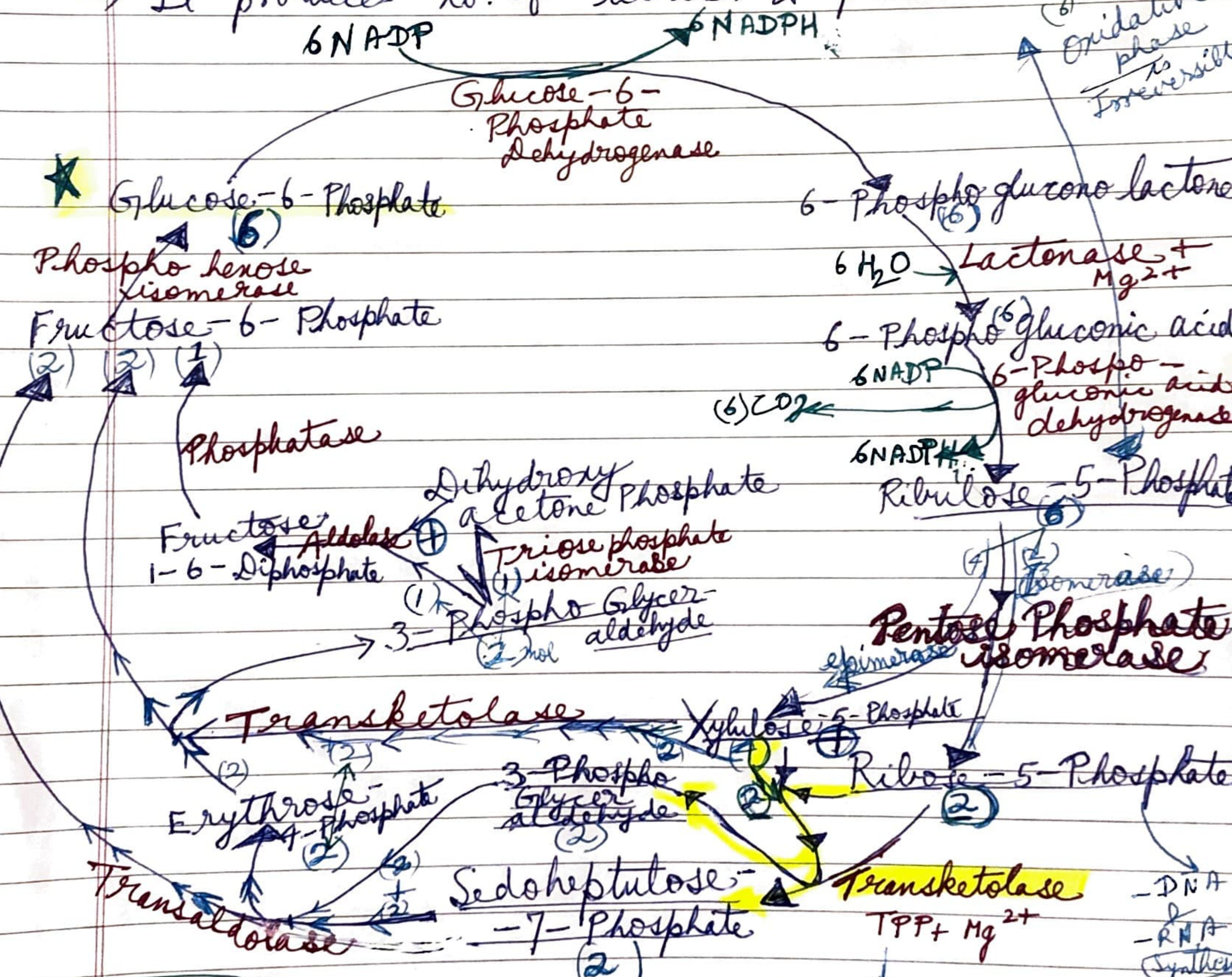
→ Production of NADPH is not linked to ATP generation in this PPP.

→ It produces ribose sugars (for Synthesis of Nucleic acids)

→ It plays imp. role in fixation of CO_2 in photosynthesis through ribulose 1-5-biphosphate (is generated)
(ribulose 1-5-biphosphate is derived from ribulose-5 phosphate & it is the CO_2 acceptor in photosynthesis in C_3 plants.

→ It provides erythrose-4-phosphate required for synthesis of shikimic acid

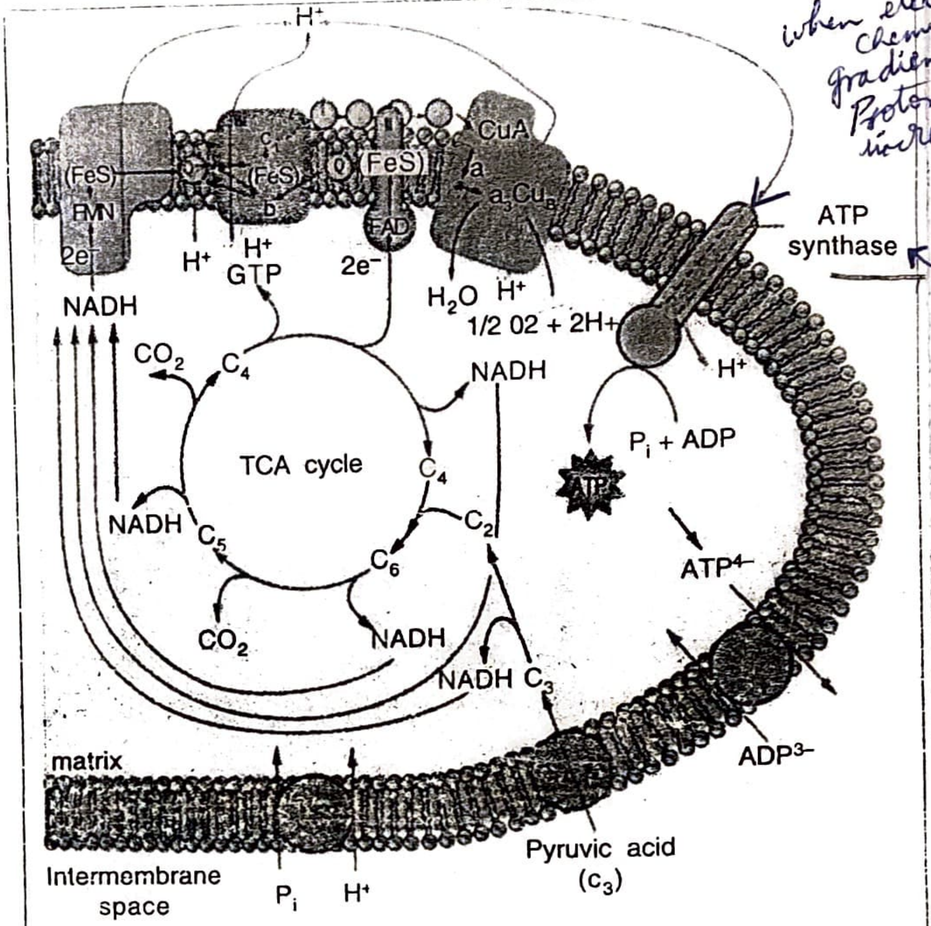
→ It produces no. of tetroses & pentoses.



6 molecules of glucose-6-phosphate that enter into HMS produce 6 molecules of CO_2 after oxidation. 12 molecules of reduced coenzyme NADPH & 5 molecules of Glucose-6-phosphate are regenerated.

TPP ↓ Thiamine Pyrophosphate

-ATP
-NAD+
-FAD
-CoA



Summary of the major activities during aerobic respiration in a mitochondrion.

when electro chemical gradient or Proton gradient increases then H^+ goes back through

Respiration: → is a vital process, occurs in living cells
→ It is a biochemical process.
→ Energy is released step by step.
→ Less than 50% energy is liberated as heat
→ There is small rise in temperature
→ Most energy is stored in ATP molecules.
→ Respiratory reactions are regulated by enzymes
→ Several intermediates are formed.
→ Oxidation takes place at the end of reaction between reduced Coenzymes & Oxygen.